A

Research Proposal

On

Noise control and Dynamic Life Rating Improvement of Rolling Bearing

Submitted by

Borse Deepak Ravindra

Under the guidance of

Dr. V. B. Tungikar

*

DEPARTMENT OF PRODUCTION ENGINEERING,

SHRI GURU GOBIND SINGHJI INSTITUTE OF ENGINEERING & TECHNOLOGY, VISHNUPURI, NANDED-431605 (INDIA)

SWAMI RAMANAND TEERTH MARATHWADA UNIVERSITY, NANDED

CANDIDATE'S DECLARATION

I hereby declare that the work proposed in this synopsis titled ñ**Noise Control and Dynamic Life Rating improvement of Rolling Bearing"** is presented on behalf of partial fulfillment of the requirement for the award of the degree of Philosophy Of Doctorate submitted to the department of **Production Engineering, Shri Guru Gobind Singhji Institute of Engineering & Technology, Nanded, India**, under the supervision and guidance of Dr. V. B. Tungikar, Professor, Production Engineering Department, SGGSIE&T, Nanded.

I have not submitted the matter embodied in this proposal for the award of any other degree or diploma.

Date: 08 /06/2016

Place: **Nanded** **(BORSE DEEPAK RAVINDRA)**

CERTIFICATION

This is to certify that the above statement made by the candidate is correct to the best of our knowledge and belief.

Dr. V. B. TUNGIKAR,

Professor,

Head of Production Engineering Department,

SGGSIE&T, Nanded-431606

Content:-

1.Abstract	3
2. Introduction	4
3. Literature survey	5
4. Objectives and Methodology	14
5. References	16

ABSTRACT

The rolling elements bearings are widely used in industrial and domestic machines. The existence of even tiny defects on the mating surfaces of the bearing components can lead to failure through passage of time. Their failure leads to economical and personal losses. The noise and vibration monitoring technique is mostly used in the industries for health monitoring of bearings. Significant studies are available in open literature for vibration analysis of healthy and defective rolling elements bearings.

Various researchers have studied the vibrations generated by bearings through theoretical model and experimentations. The researchers have developed the dynamic model of shaft bearing systems for the theoretical studies. This proposal states the idea of necessity in real life problems bearing industries are facing. Based on that the mathematical model , causes of noise can be picked up. Redesigning of the cage element and surface texture parameters will lead to minimise the intensity of noise in real life electrical vehicles.

To perform the validation by Experimental analysis of ball bearing to analyze the effect of cage modified design and texture parameters on Noise of bearing will be done in future research work. Apart from it, enhancement of dynamic life rating in existing ISO standard bearing is the burning goal for all manufacturers. Proposal will focus on the improvement of life rating and atomisation of Rolling bearing with the help of Matlab tool to minimise the design lead time while developing the new product design.

Proposal states that that intensity of Noise in high class Electric Car, will be resolved through this research work. Apart from this, new era will be developed for Indian manufacturers to get the idea of surface texture design and cage design to control the noise & vibration of exsting rolling bearing.

INTRODUCTION

Bearing is most important element of entire automobile sector. In this dynamic world without bearing, no smooth movement is possible. Bearing is not only bear the load but also provide anti friction phenomenon. Entire automobile sector runs on smoothness of one mechanical *component which posses the unbreakable, flexible, easily mountable, self lubricating properties.

Huge research and innovations has been going on since 1784 when bearing was found by scientist Philip & ironmaster.

Initially when bearing was designed the main objective was to just smoothen the rotational motion. Ball should rotate on race ways; it should survive the load etc. But as time grows the necessity generated, like the popular quotes ñnecessity is mother land of innovationò.

Lot of improvements has been done for smoothness of rotation of balls, especially on its hardness properties, toughness of cages, surface roughness quality etc. Many times the challenges came but researches had resolved it with prototype modelling with experimental validation. Current scenario says that the bearing is at highest position where no such major complexities are more. But OEM i.e. original equipment manufacturer are moving toward more and more comfort and luxuries automobiles. Day by day new complex type of automobile designs as well as industrial machineries components are playing vital roll in globally and are making great impact on Tier 1 and Tier 2 industries. Specially on bearing manufactures in India NBC, SKF, FAG, TImkin, NRB this top manufacturer facing great problems of Vibration and Noise Control issues in Bearing for New Electric Automobile vehicles designed by International OEM like BMW, Renault, Nissan etc. So, lot of challenges are in Noise control of such specific bearings. Hence it is most recent wide research area like Lubrication and New Product Development of rolling Bearings. Vibration and noise control with the modification of geometrical parameters in bearing design is big scope for research to achieve the fulfilment of OEMs requirements.

LITERATURE SURVEY

So many researchers have worked on Vibration and Noise control activities of rolling bearing. Some of literature articles on analytical and experimental work are as follows:

2.1 Analytical Work

Patil M S, Mathew J, Rajendra kumar P K [1] discussed about the bearing vibration signature analysis technique to detect the fault. Tutorial overview for the causes is explained in this article. Defective bearing may lead to deterioration of bearing life. Various methods are utilized for bearing defect detection and its diagnosis. Simulation of vibration measurement is done in both Frequency and time domain. Authors are discussed about the recent trend for bearing defect detection.

Tandon N, Choudhury A [2] This article is review of vibration and sound measurements techniques to detect the defect in rolling bearings. Categories of defect in Localized and distributed is considered by authors. Article is full of explanation of causes of noise and vibration in rolling bearings. Vibration measurement techniques are discussed in details. With the high frequency resonance signal process techniques, measurements of vibrations in frequency and time domain are explained. Article has been reviewed the sound pressure, sound intensity and acoustic emission techniques to understand the detection of defects in bearings. Review of recent trends in defect detection in rolling bearings is mentioned. Wavelet transform method and automated data processing have also been reviewed.

Patel V N, Tandon N, Pandey R K. [3] Discussed about the vibration analysis of defective rolling deep groove ball bearings. The single and multiple defects are on inner and outer race. Dynamic model is proposed for this type of defective rolling bearing. Mathematical modelling has been done on analysis defective bearing with the mass consideration of housing, shaft, race and balls. Runge-kutta method is used to solve the governing equation of motion for coupled its solution. Both time and frequency domains are used for measurement of vibration of shaft, balls and housing. With the help of healthy and defective deep groove ball bearing, experiment has been carried out to validate the results obtained in coupled

solution of governing equations. Using theoretical and experimental analysis, characteristics defect harmonics & frequencies are thourouly investigated. Vibration spectra for both single defective and multiple defective bearings are evaluated. Article clearly shows the spectra of vibration for multiple defects on races reveals higher velocity than single defect on races of rolling bearing. The article reports the well correlation among all type of investigation of defective bearing analysis such as vibration analysis, experimental & theoretical. This dynamic model governed by authors can be utilized for the prediction and study of vibrations of healthy and defective ball bearings.

Lyons R G. [4] To assist the working Digital single processor engineers, the following remarkable sections are thoroughly explained in this book by author:

- Realistic direction in building discrete matched filters, differentiators, integrators
- Statistical measures descriptions of signals, variance decreased by Way of averaging, and computing techniques of real-world signal-tonoise Ratios (SNRs)
- A noticeably expanded division on sample rate conversion (multirate systems) with its related filtering
- Development of fast convolution (FIR filtering in the frequency domain)
- Improved material covering methods for analyzing the performance and Improvement of digital filters in modern processing systems,
- extended images of industry-standard binary number formats are explained used
- several accompaniments to the popular ñDigital Signal Processing Tricksò section

McFadden P D, Smith J D. [5] this article deals with the Development of the mathematical model is carried out to elaborate the vibration generated because of under constant radial load single point defect on the inner race of a rolling element bearing. The mathematical model deals with the properties of bearing like load distribution, shaft speed, bearing geometry, the exponential decay of vibration and transfer function. Performance of the model is Satisfactory confirmed by comparison of measured demodulated vibration and predicted vibration

Patel V N, Tandon N, Pandey R K. [6] This article deals with the improvement in the detection of defect of rolling bearings with the help of ANC adaptive noise cancelation, Mathematical multistage morphology MMM and self adaptive noise cancellation SANC as a

external vibrations. This improvement is due to difficulty in the presence of external vibrations for identifying the signals generated in defective rolling bearings of industrial machines. The external random vibration is introduced to the housing and shaft assembly. The bearings contain artificial defects crated on its raceways to experiment. An electromechanical shaker is used to generate the artificial random vibration to analysis the bearing defect response. Due to application of adaptive noise cancelation, Mathematical multistage morphology & self adaptive noise cancellation signal to external acoustic vibration ration is significantly enhanced. In the vibration spectrum the defect frequencies are clearly identified. Article contains the adaptive noise cancelation method LMS least mean square flowchart with & without function of signum is used. In the bottom hat transform and operations of closing triangular structural elements are used in Mathematical multistage morphology method. Least mean square algorithm with signum functioning is more efficient and effective in error minimisation method in comparison of least mean square algorithm without function of signum. Articles showed that the Mathematical multistage morphology filter is much efficient for noise minimization techniques.

Patel V N, Tandon N, Pandey R K. [7] this paper deals with usage of Doffing oscillator as well as envelope analysis to detect the local defects presented on races of deep groove ball bearing in the occurrence of external vibrations. With the help of test rig experiments have been performed to capture the test bearingôs vibration signals. Electromagnetic shaker generate external vibration according to the requirements and it has been imparted to the test bearing housing. Using spectral kurtosis, the centre frequency has been chosen for the filters length of 64 and 32 for dissimilar bandwidths in envelope analysis. The selection of centre frequency and bandwidth is the main dependency criterion for defect detection in envelope analysis. it has been confirmed and established through this study. The comparison is made between selected centre frequency spectra and several bandwidths for identification of defective frequency and also it have been analyzed and compared. At the critical value of disturbing periodic force the system defined by the duffing equation entered into the periodical state from the chaotic state in the presence of defective bearing signal. The author has identified the state change using the Duffing equation Lyapunov exponents and phase plane trajectories. Author observed that the information regarding the defect harmonics and defect frequencies has been inflated by envelope spectrum. Despite the fact that, the Duffing oscillator only assures the existence of defect frequencies by representing negative Lyapunov exponents and closed phase plane trajectories. It is worth to mention here that usage of

Duffing oscillator might be preferred, for speedy assessment about the existence of defects on track races of rolling element bearings.

Su, Y. T., Lin, S. J., [8] In this article the investigation has been carried out to characterized frequency of vibration and harmonics of vibrations for a defective rolling bearing under various loadings. The dynamic motion equation is further exaggerated to elaborate the vibrations of rolling bearing occurred by multiple or single defect located at random positions, under miscellaneous loading conditions. On the strength of the mathematical model, with a prototype of ñidentical frequency spacing allocationò the vibration spectrum is a discrete one. In the demodulation spectrum, there are peaks at defect harmonics and the defect frequency. In the region of each peak, there are side bands related to the periodic properties of the loadings and transmission path. The validity of the analytical study is confirmed by an extensive evaluation of experiments. An extensive evaluation of experiments confirms the validation of analytical study.

Sopanen, J., Mikkola, A., [9] Author proposed the mathematical modelling of DG rolling ball bearing with six degrees of freedom. Authors studied the descriptive analysis of nonlinear hertizian contact deformation and elasto hydrodynamics. The inputs of this derived dynamic model of bearings are geometry, material properties and diametric clearance. With the help of displacements and relative velocities between outer and inner ring bearing force and torque components are calculated. Waviness of outer and inner rings and flakes of raceways are considered as a distributed a localised defect in this article. Between the rotor and the housing dynamic model can be useful in the rotor dynamics computer code and general multi body or rotor dynamics as an interference element. Numerical evaluations obtained from the proposed dynamic model are validated with the literature article part number two. Author state the conceptual dynamic model to justify his results through validation.

Sopanen, J., Mikkola, A., [10] in this article mathematical model of dynamics of rolling ball bearing proposed by authors is analysed and implemented with the help of mercantile multi body software package ADAMS. Diametric clearance of bearing is provided as radial clearance to it for adjustment of bearing fitment. This radial clearance is studied by author due to its great impact on vibration of bearing and also its noise response of the rotor-rollng bearing assembly. On the level of natural frequencies and vibration diametric clearance make greater impact. Out of roundness also expressed in terms of low order waviness is responsible to vibrate the bearing with certain frequency and mortification factor of rotational speed. Similarly vibration at the ball pass frequency of inner ring and ball pass frequency of

outer ring is close to the waviness where various excitations produce sum and difference frequencies. Simulation result is validated by authors with numerical and other experimental. At bearing defect frequencies, localised and distributed defects in inner rolling ring and outer rolling ring are found to generate vibrations.

Arslan, H., Aktürk, N. [11] Author investigate the mathematical model on shaft bearing assembly to determine and evaluate the magnitude of vibrations for double row angular contact ball bearing at two modes. The author has chosen the defective piece of angular contact rolling ball bearing and non defective i.e. Healthy bearings. Mass spring system is considered in this article for shaft bearing assembly. Under dynamics conditions the spring mass assembly system presents non linear characteristics of vibration response. Mathematical modelling of motion of rotation of angular contact ball bearing in axial as well as in radial direction has been developed for rolling element and shaft assembly and evaluation & simulation of nonlinear mathematical model is solved by computation programming. Also author studied the vibrational response of localised and distributed defects on inner and outer race as well as cages & balls. In radial direction of angular contact rolling ball bearing vibration response of rolling element is studied in tie and frequency domains. In the frequency spectra authors has shown the characteristics defect frequencies and their components. Reasonable qualitative agreement has been shown by author on comparison with derived model and similar studies.

Ashtekar, A., Sadeghi, F., Stacke, L., [12] In this article, with the help of equation of motion mathematical model for angular contact and deep groove ball bearings has been modelled to examine the influence of race defects on the motions of bearing parts like cages, balls, inner and outer races. The author has developed the dynamic model In order to determine the deflection & force association between a dented semi-infinite domain and an ellipsoid. Model has been designed to determine the effects deterioration of performance rolling bearing in the existence of dents. Whenever a ball/dent interaction occur, the well-known Hertzian force-deflection relationship has been replaced Incorporation of The force-deflection relationship in the bearing dynamic model for dented surfaces. In this article, all bearing components like cages, balls, outer & inner races have six degrees-of-freedom. To determine the motions of all bearing components Newtonôs laws are used, and with a variable or constant step size, an explicit fourth order Rungeï Kutta algorithm was utilised to integrate the complex motion equations. A simulation of Dynamic model elaborates the effect of inner race speed, dent size and dent location on bearing components. The results shows that surface irregularities

and defects like dent have a harsh effect on performance of bearing motion as well as the forces. In addition, for high-speed applications these effects are even harsher. Demonstration of The results also express, that a single dent can influence the motion and force right through the whole rolling bearing and its components. On the other hand, the dent position dictates the intensity of influence on cages, balls, inner & outer rails.

2.2 Experimental work

Jing Liu, Yimin Shao, W. D. Zhu, [13] In this article author showed the impact of defect sizes such as width depth and position of localised surface defect on deep groove ball bearing vibration characteristics. However, in previous defect models Author has not consider the time varying contact stiffness between defect and ball , effect of defect depth and the relationship between defect sizes and time-varying contact stiffness. In this work, for replacement of the Hertzian forceï deflection association to explain the ball-line contact between the defect and ball edge, a new defect model is presented with consideration of a new forceï deflection relationship. The Author has considered both times-varying contact stiffness and the time-varying displacement impulse. Through the mathematical modelling, the relationship between defect sizes and the time-varying contact stiffness are obtained. Previous models donôt deal with the effect of defect size. Author made the relationship between depth of defect and its impact on response of vibration of deep groove ball bearing. Simulation of this model is compared with previous one. This shows the reasonable qualitative agreement of simulation result with the help of computational programming for dynamic simulation of the rolling elements of deep groove ball bearing. A more realistic impulse can be predicted by developed mathematical model and its dynamic simulation of deep groove ball bearing. Experimental validation has been carried out by author in this paper.

M. Craig, T.J. Harvey et. Al [14] paper discuss about a new condition monitoring technique is under development which is based on electrostatic charge. This was originally employed for the detection of debris in the gas path of jet engines and gas turbines, and is now being developed for lubricating systems. Previous investigations have demonstrated the viability of this technique in dry and lubricated Tribo-contacts using laboratory-based equipment. This paper reports on the evolution of wear during a tapered roller bearing test, using a suite of

condition monitoring techniques, that incorporated electrostatic wear-site sensors to identify the charge during surface wear and oil-line sensors to detect debris in oil scavenge lines. The multi-sensor arrangement also included a vibration accelerometer, thermocouples, inductive and ferromagnetic particle counters. Additionally, oil samples were taken during various stages of the test and were analyzed for sub-100 mms debris content. Off-line debris analysis included optical particle counting, ferrography, spectrometric oil analysis and electron microscopy. Further tribological assessments included mass loss calculations and photographic evidence of damage. During the initial 7 h, running-in wear was identified by dynamic wear site charge, acceleration and temperature. Also at this time, increases in oil-line charge correlated with debris detection by the inductive sensor, optical particle counter and photographic analysis. Following running-in, benign wear was indicated by a reduction in wear site charge, acceleration and temperature, as well as reductions in oil-line charge, inductive and optical particle counts. Around 42 h, increases in inductive and optical particle count were considered to be an early indicator (or precursor) of the impending wear out phase. At 53.5 h, wear out was identified by increases in wear site charge, acceleration and temperature. Evidence of wear debris was shown by increases in oil-line charge, inductive and ferromagnetic particle count. The debris was further corroborated by optical particle count, ferrography and spectrometry. The test was then stopped after 63 h and post-test analysis confirmed outer race and roller spall*ation.

Mohsen Nakhaeinejad, Michael D. Bryant [15] Multibody dynamics of healthy and faulty rolling element bearings were modeled by authors using vector bond graphs. A 33 degree of freedom (DOF) model was constructed for a bearing with nine balls and two rings (11 elements). The developed model can be extended to a rolling element bearing with n elements and _3_n_ DOF in planar and _6_n_ DOF in three dimensional motions. The model incorporates the gyroscopic and centrifugal effects, contact elastic deflections and forces, contact slip, contact separations, and localized faults. Dents and pits on the inner race and outer race and balls were modeled through surface profile changes. Bearing load zones under various radial loads and clearances were simulated. The effects of type, size, and shape of faults on the vibration response in rolling element bearings and dynamics of contacts in the presence of localized faults were studied. Experiments with healthy and faulty bearings were conducted to validate the model. The proposed model clearly mimics healthy and faulty rolling element bearings.

Mr. K H Munde, Dr. S B Thakre [16] article state that vibration analysis is one of the most usual methods utilized to evaluate the conditions of bearings in an operating machine. Such measurements may be used for machines with bearings in new condition as well as for machines whose bearings are deteriorating and approaching the end of their useful lifespan. If a machineôs vibration response to known excitation forces has been determined through techniques such as finite element analysis and modal analysis, then vibration measurements during service can determine the dynamic characteristics of the forces working on the car. Vibration data can likewise be used to know forcing characteristics and the condition of machine parts, mainly bearings. The paper highlights the work done by various researchers for bearing fault detection.

Dipen S. Shaha, Vinod N. Patel, [17] this paper reviews, Mathematical modeling of rotating bearing in absence and presence of distributed and local defects. In domestic and industrial machines, the rolling elements of bearings are broadly used. Through the passage of time subsistence of even tiny defects on races of bearings components may lead to damage and failure of bearing. Personnel and economical losses are result of such failures. For health monitoring of bearings in the industries, the engineers mostly uses the vibration monitoring technique. The fault detection has been improved by the signal processing techniques like high frequency resonance technique (HFRT), cyclic autocorrelation, envelope analysis and wavelet transform, for vibration analysis of defective and healthy rolling elements bearings, Variety of studies is present in open literature. Through theoretical model and experimentations, the dynamic model has been developed by various researchers. Vibrations generated by bearings are studied of several researchers. These article summaries the fault detection improvement techniques in rolling bearing

OBJECTIVES AND METHODOLOGY

Based on the real life Automobile requirements of the Noise control and Life rating following objectives are proposed:

Objectives:

- To perform the Mathematical modeling of Noise generated by elements of bearing with respect to surface texture parameters and cage design
- To perform the simulation of Texture parameters of race track and its impact on Noise
- To perform the validation by Experimental analysis of ball bearing to analyze the effect of cage modified design and texture parameters on Noise of bearing
- To perform the improvements of the Dynamic life rating and Modified life rating of rolling ball bearing
- To perform the Development of the design tool automation module for Deep groove ball bearing series in Mat Lab (Matrix Laboratory)

Research Outcomes:

- Recent critical Noise issues in high class Electric Car, will be resolved through this research work
- Development of the relation between noise and texture parameters will easily identify root cause of profile and its effect on the magnitude of Noise.
- Proposed techniques and its simulation help Indian manufacturers to improve the dynamic Load rating and the life rating of rolling bearings
- Full automation of deep groove ball bearing design will help the manufacturing industries to shortly complete the entire design procedures to minimize the Lead Time for evaluation of critical and complex parameters.

METHODOLOGY

- **Mathematical Modelling:**

  Mathematical Modelling will be done to determine the relation between these parameters of inner and outer race track and noise. With the help of Hamilton and langrangian equation the model will be developed. High frequency vibration is nothing but Noise. The transverse vibrations will be modeled with the help of Multibody dynamics and nonlinear differential equations.

- **Runge kutta method:** Runge kutta method will be used for solving the higher degree non homogeneous ordinary differential equation with time period. This method is implicit and explicit iterative techniques which are used for determining approximated solutions of non linear ordinary differential equations.
- **Simulation**: Matlab Editor and Matlab simulink software packages will be used for simulation of mathematical modelling. For solving the OD Equations ñode23ò or ñode45ò will be used to simulate the non homogeneous ordinary differential equations.
- **Time domain and frequency domain :**
  Time domain and frequency domain are two types of analysis domain where the time vs. displacement and frequency vs. displacement is measured respectively. Time domain & FFT analysis will be used in Simulation of response of rolling bearing vibration.

- **Experiment**: Assembled bearing consists of cage, rivet, balls, inner and outer races. In that situation it is really interesting to evaluate performance the texture parameters, cage design by experimentation. The texture parameters will be measured by TalyHobson Machine. The experiment will be done on Noise Measuring machines. The Noise control machine measures the noise with high speed rotation of the bearing and its amplitude during the rotation. So it would be easily helpful to validate the results obtained through surface texture parameters and cage design.

REFERENCES:

[1] Patil M S, Mathew J, Rajendra kumar P K., Bearing signature analysis as a medium for fault detection: a review, ASME Transaction on Tribology 2008; 32 p. 130014001-014007.

[2] Tandon N, Choudhury A., A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings, Tribology International 1999; 32 p. 469-480.

[3] Patel V N, Tandon N, Pandey R K., Defect detection in deep groove ball bearing in presence of external vibration using envelope analysis and Duffing oscillator, Measurement 2012. Vol. 45 p. 960-970.

[4] Lyons R G. Understanding digital signal processing, Pearson Education; 2005 ISBN 81-297-0534-6.

[5] McFadden, P. D., Smith, J. D., Model for the Vibration Produced by a Single Point Defect in a Rolling Element Bearing, Journal of Sound and Vibration 96, 1984. p. 69-82.

[6] Patel V N, Tandon N, Pandey R K., A dynamic model for vibration studies of deep groove ball bearings considering single and multiple defects in races. ASME Transaction on Tribology 2010

[7] Patel V N, Tandon N, Pandey R K., Improving defect detection of rolling element bearings in presence of external vibrations using adaptive noise cancellation and multiscale morphology, Proc. Instn. Mech. Engrs. Part J: J. Eng. Tribol 2012; 226 p. 150-162.

[8] Su, Y. T., Lin, S. J., On Initial Fault Detection of a Tapered Roller Bearing: Frequency Domain Analysis, Journal of Sound and Vibration 155, 1992. p. 75ï 84.

[9] Sopanen, J., Mikkola, A., Dynamic Model of a Deep-Groove Ball Bearing Including Localized and Distributed Defects. Part 1: Theory, Proc. Instn. Mech. Engrs., Part K: Journal of Multi-Body Dynamics 217, 2003. p. 201-211.

[10] Sopanen, J., Mikkola, A., Dynamic Model of a Deep-Groove Ball Bearing Including Localized and Distributed Defects, Part 2: Implementation and Results, Proc. Instn. Mech. Engrs., Part K: Journal of Multi-Body Dynamics 217, 2003. p. 213- 223.

[11] Arslan, H., Aktürk, N., An Investigation of Rolling Element Vibrations Caused by Local Defects, Journal of Tribology Transaction of ASME 130, 2008. p. 041101-1-041101-12.*

[12] Ashtekar, A., Sadeghi, F., Stacke, L., A New Approach to Modelling Surface Defects in Bearing Dynamics Simulations, Journal of Tribology Transaction of ASME 130, 2008. p. 041103-1-041103-8.

[13] Jing liu, yimin shao, w. D. Zhu, A New Model for the Relationship Between Vibration Characteristics Caused by the Time-Varying Contact Stiffness of a Deep Groove Ball Bearing and Defect Sizes, Journal of Tribology, ASME, Vol. 137, 2015

[14] M. Craig , T.J. Harvey, R.J.K. Wood, K. Masuda , M. Kawabata, H.E.G. Powrie , Advanced condition monitoring of tapered roller bearings, Part 1, Tribology International 42, 2009. p1846ï 1856

[15] Mohsen Nakhaeinejad, Michael D. Bryant, Dynamic Modeling of Rolling Element Bearings with Surface Contact Defects Using Bond Graphs, Journal of Tribology ASME Vol. 133, 2001

[16] Mr. K H Munde, Dr. S B Thakre, A Review on Bearing Fault Detection by Vibration Signature Analysis, International Journal of Innovative Research in Science, Engineering and Technology, Vol. 4, Issue 6, June 2015

[17] Dipen S. Shaha, Vinod N. Patel, A Review of Dynamic Modeling and Fault Identifications Methods for Rolling Element Bearing, Procedia Technology 14, 2014 . p 447 ï 456